Fermi National Accelerator Laboratory

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Computation of the Tevatron Luminosity Using Measured Machine Parameters

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Computation of the TEVATRON Luminosity Using Measured Machine Parameters[1]

At a collider the luminosity $\mathcal{L}$ is needed to extract the cross section from the measured reaction rate. The luminosity can be determined in an experiment by measuring the rate of a reaction with a known cross section. This note describes an alternative calculation of the luminosity based on measurements made on the stored beam in the TEVATRON. The measurements necessary for the calculation, and which must be made on each of the p and $\overline{p}$ bunches, are the intensity and the transverse and longitudinal extent of each of the bunchs.

Data on the properties of each of the 12 (6 p and 6 $\overline{p}$) bunches in the TEVATRON were collected during the last collider run and stored (along with the associated time and date) in a relational data base (the SHOTDB data base). The information stored in the data base was the only source of the machine data used in the following calculations.

Unfortunately all the stored data are not the actual measured quantities. The stored data are the transverse and longitudinal emittances calculated by the console program T106 from the measurements rather than the measured bunch lengths and the transverse widths of the bunches.

The transverse emittances were calculated using the bunch width, σ, as measured by the flying wires, and the computed value of the lattice functions β and the dispersion η at the location of the flying wires. The particular lattice, *viz.* mini-β, fixed target *etc.* is determined from a knowledge of the current in B0Q1 and the beam energy.

In order to calculate the longitudinal emittance the measurements of the bunch length measured with the SBD; the r.f. voltages (called T:RFSUM and T:RFSUMA); the beam energy and the calculated value of the transition $\gamma(\gamma_t)$ were used.

To calculate the luminosity we have to extract, for each bunch, the following information from the data base:

[1]Work supported by the U.S. Department of Energy under contract No. DE-AC02-76CH03000.

- The calculated normalized (95%) transverse beam emittances ϵ_h, ϵ_v.
- The longitudinal emittance ϵ_l.
- The measured beam intensity.
- The beam energy.
- The r.f. voltages T:RFSUM and T:RFSUMA.

As noted above the emittances are the product of calculations performed by T106 and are dependant on the lattice parameters. The values of the lattice parameters used in T106 changed during the run. (*The lattice parameters did not change! What changed was what we thought their values were.*) In order to calculate the luminosity we must recover, from the stored values of the emittances, the measured beam properties. To do this requires that we know the lattice functions and the other parameters, (viz the energy and the r.f. voltages), which were used in the original calculation. Fortunately the lattice parameters have been preserved in the coding for the T106 console program. The other needed parameters can be retrieved from the SHOTDB data base. It was therefore possible to reconstruct the values of the σ for the flying wires measurements and the SBD measurements of bunch length.

Having reconstructed the original measurements of the beam σ it is straight forward to recalculate the emittances using our best estimate for the values for the lattice parameters. [2]

The following discussion is limited to measurements made with the TEVATRON energy at 1.8 TeV and with the mini-β lattice. The data are from store 1728 (11/6/88) to the end of the collider run, store 2284 on 5/31/89.

It must be recognized that there is very little redundancy in the measurements used in these calculations. Nor is there a good way of monitoring closely the performance of the devices used in the measurements or their calibrations. Thus care must be used when approaching the data and further we must look at the results of the calculations to identify bad or suspect data.

The one place where we do have redundancy is in the measurement of the longitudinal emittance ϵ_l. It can be calculated from the measurement of

[2] The lattice functions and γ_t have been calculated using TEVLAT and the MTF measurements of the high order multipoles for the dipoles and quadrupoles and the measured strengths of the quadrupoles.

the bunch length made by the SBD (ϵ_l(SBD) and from the measurement of dp/p calculated from the flying wire data (ϵ_l(WIRE)). In figure 1a and figure 1b are plotted ϵ_l(WIRE) vs ϵ_l(SBD) for protons and anti-protons. There are obviously anomalous data which are almost certainly due to bad data from the flying wires. [3]

There are no any other redundancies in the data but we can still look for consistencies in an attempt to identify other anomalous measurements.

It is generally accepted that because of the coupling between the horizontal and vertical planes. the TEVATRON beam is round i.e. $\epsilon_v = \epsilon_h$. In figures 1c and 1d are plotted ϵ_v vs ϵ_h for protons and anti-protons.

The results from the calculation of the luminosity include only those measurements that survived after a cut was imposed on the ratio ϵ_l(WIRE)/ϵ_l(SBD). This was done to insure that the WIRE data are consistent with the SBD measurements. A cut was also imposed on the ratio of ϵ_v/ϵ_h in an attempt to remove other bad measurements.The values of all cuts is shown in Table I.

The effect of these cuts can be seen by comparing the plots in figure 1 and figure 2.

Even after the cuts are applied to the data there are still problems. The longitudinal emittance as computed from the SBD data is, on the average, more than 20% larger than that computed from the wire measurements for the proton bunches and 10% larger for the anti-protons. While an error in the lattice functions at A17 and C48 could account for the difference between the SBD measurements and those based on the flying wires. the difference between protons and anti-protons suggests that part of the discrepancy could be due to an to an intensity dependent error (the protons and anti-protons have significantly different intensities) of the SBD determination of the bunch length σ_l.

Similarly ϵ_v is $\approx 10\%$ larger than ϵ_h. Here there is no significant difference between the protons and the anti-protons. If there is no systematic error in the σ (which could arise due to problems with the detectors recording the particles scattered from the wires) from the flying wires then the difference could be due to an error in either or both of the β functions at C48.

Our inability to understand these inconsistancies in the data limit our

[3]The anomalous ratio is particularly apparent near store 2000 where the reconstructed σ show unusual values for the σ of the HA17 wire.

ability to confidently measure the luminosity.

We will present the calculations for the TEVATRON operating at an energy of 1.8TeV with the mini-β lattice and where there were 6 p and 6 $\bar{p}$ bunches in the TEVATRON. In order to calculate the luminosity $\mathcal{L}$ we require, in addition to the emittances,

- The bunch intensities measured with the SBD.
- The values of the lattice functions β and α at the interaction point.
- The values of the dispersion functions η and η' at the interaction point.

The calculation of $\mathcal{L}$ makes use of the the transverse emittances calculated from the flying wires, the dp/p derived from the SBD data and incorporates an integration over the longitudinal extent of the beam.

The calculated values for the luminosity can be compared with the value for the luminosity measured at CDF, viz. C:B0LUMP. The comparison is shown in figure 3. It must be noted that no correction has been made to any of the measured quantities for possible miscalibrations. These data can be fit with a quadratic form viz.

$$\mathcal{L}_{cal} = a_0 + a_1 \times \mathcal{L}_{meas} + a_2 \times \mathcal{L}^2_{meas} \tag{1}$$

Table II contains the fitted values of the coefficients for the entire data sample and for two subsets of the data in order to see if there where any major changes over the 7 month period from Nov. 1988 to May 1989. The fit is good, the rms deviation of the fitted value from the calculated luminosity being $\approx \pm 0.02 \times 10^{30}/\ \mathrm{cm}^2 \cdot$ sec. There is no strong dependence of the coefficients on the store number. The intercept of the fitted curve is ≈ 0 in all cases. The coefficient of the linear term is significantly different from 1 and there is also a significant negative quadratic coefficient in the fit. This means that the value of $\mathcal{L}$ calculated from the measurements made on the TEVATRON are lower that those measured at CDF for values of the measured luminosity greater than $\approx 1.25 \times 10^{30}\ \mathrm{cm}^2\cdot$ sec.

Since a_0 in the fits is ≈ 0 we can also plot (figure 4) the ratio $\mathcal{L}_{meas}/\mathcal{L}_{cal}$ with $\mathcal{L}_{meas}$. in order to see more clearly the quadratic term in the fit. The obvious slope seen in figure 4 is just a reflection of the quadratic term seen in the fit to the data in figure 3.

Any scientific calculation of the luminosity must include an estimate of the error. Table IV contains a list of the quantities (Q) that go into the calculation of the luminosity, an estimate of their systematic and random uncertainties and their contribution to the uncertainty in the luminosity. The resulting uncertainty from the measurement uncertainties is $\approx 1.3\%$ while the uncertainty due to systematic uncertainties is $\approx 11.4\%$. The uncertainty due to the ascribed errors in measurement is quite comparable to the $\approx 2\%$ spread seem in the comparison of the calculated luminosity and the measured luminosity (the error in the measured luminosity is $\approx 0.5\%$).

The factor that contributes most to the uncertainty in $\mathcal{L}$ is the calibration of the SBD measurements of the bunch intensities. Also contributing significantly to the error in the calculated luminosity are the uncertainty in the measured wire σ (particularly the vertical wire σ at C48 because of the relatively small value of β_y) and the uncertainties in the lattice functions at the wires and at B0. We also find that there is a significant contribution to the error on $\mathcal{L}$ from the measurements of the SBD of the bunch length and the calculated value of dp/p using the measured bunch length and the r.f. voltage (due to the systematic uncertainty in the voltage).

It is clear that if we wish to improve the uncertainty with which we measure the luminosity it will be important to improve the calibration of the SBD in measuring the length and intensities of the bunches. A better determination of the lattice functions would also improve the accuracy of the calculation. This can be done by with more, and better, measurements of β, not only at the wire locations and the interaction points, but at enough other points to constrain the model used to calculate the lattice functions. The error could also be reduced if β at the vertical wire were larger. This might require having the vertical wire at a different location from the locations of the horizontal wires.

It is also important to check the calibration of the various devices over the range of normal working conditions, including energy.

Table I

Cut Intervals

	p		$\overline{p}$	
Quantity	min.	max.	min.	max.
ϵ_h/ϵ_v	0.808	0.979	0.758	0.960
$\epsilon_l(\mathrm{WIRE})/\epsilon_l(\mathsf{SBD})$	0.647	0.912	0.592	1.129

Table II

Fit of C:B0LUMP vs the Calculated Luminosity

$$\mathcal{L}_{cal} = a_0 + a_1 \times \mathcal{L}_{meas} + a_2 \times \mathcal{L}_{meas}^2$$

Range of Stores	a_0	a_1	a_2
1728-2279	+0.013	1.087	-0.077
1728-2005	+0.022	1.091	-0.081
2011-2279	-0.013	1.120	-0.090

Table III

Fit of C:B0LUMP vs C:B0LUMP/Calculated Luminosity

$$\mathcal{L}_{meas}/\mathcal{L}_{cal} = b_0 - b_1 \times \mathcal{L}_{meas}$$

Range of Stores	b_0	b_1
1728-2279	0.887	0.089
1728-2005	0.864	0.104
2011-2279	0.921	0.064

Table IV
Contributions of Measured and Calculated Quantities to the Error in the Luminosity

Values used:
Energy 900 GeV
Bunch Intensities

$N_p = 52 \times 10^9$

$N_{\overline{p}} = 20 \times 10^9$

Normalized emittances

$\epsilon_h(p) = \epsilon_h(\overline{p}) = 20$ mm-mr

$\epsilon_v(p) = \epsilon_v(\overline{p}) = 25$ mm-mr

$\epsilon_v(p) = \epsilon_v(\overline{p}) = 3.5$ eV-sec

Luminosity (1 bunch on 1 bunch)

1.22×10^{29}

Variable Q	Value	δQ Systematic	$\delta\mathcal{L}/\mathcal{L}$	δQ Random	$\delta\mathcal{L}/\mathcal{L}$
Bunch Length	54.6 cm	5%	-2.9%	1cm	-0.5%
r.f. Voltage	1.2MV/turn	5%	-0.6%		
HC48 Wire Sigma	0.759 mm			20μ	-1.0%
VC48 Wire Sigma	0.551 mm			20μ	-1.8%
HA17 Wire Sigma	1.32 mm			20μ	+0.1%
β_h(C48)	164 m	5%	−1.8%		
β_h(A17)	196 m	5%	-0.0%		
β_v(C48)	69.9 m	5%	-2.5%		
β_h(B0)	0.55 m	5%	-1.1%		
β_v(B0)	0.53 m	5%	-1.5%		
α_h(B0)	−0.124	5%	+0.0%		
α_v(B0)	-0.049	5%	-0.0%		
η(C48)	0.595 m	5%	+0.1%		
η(A17)	6.95 m	5%	-0.0%		
η(B0)	0.197 m	5%	-1.3%		
η'(B0)	-0.145	10%	-0.0%		
Bunch Intensity		5%	+10.2%	1×10^9	+0.5%

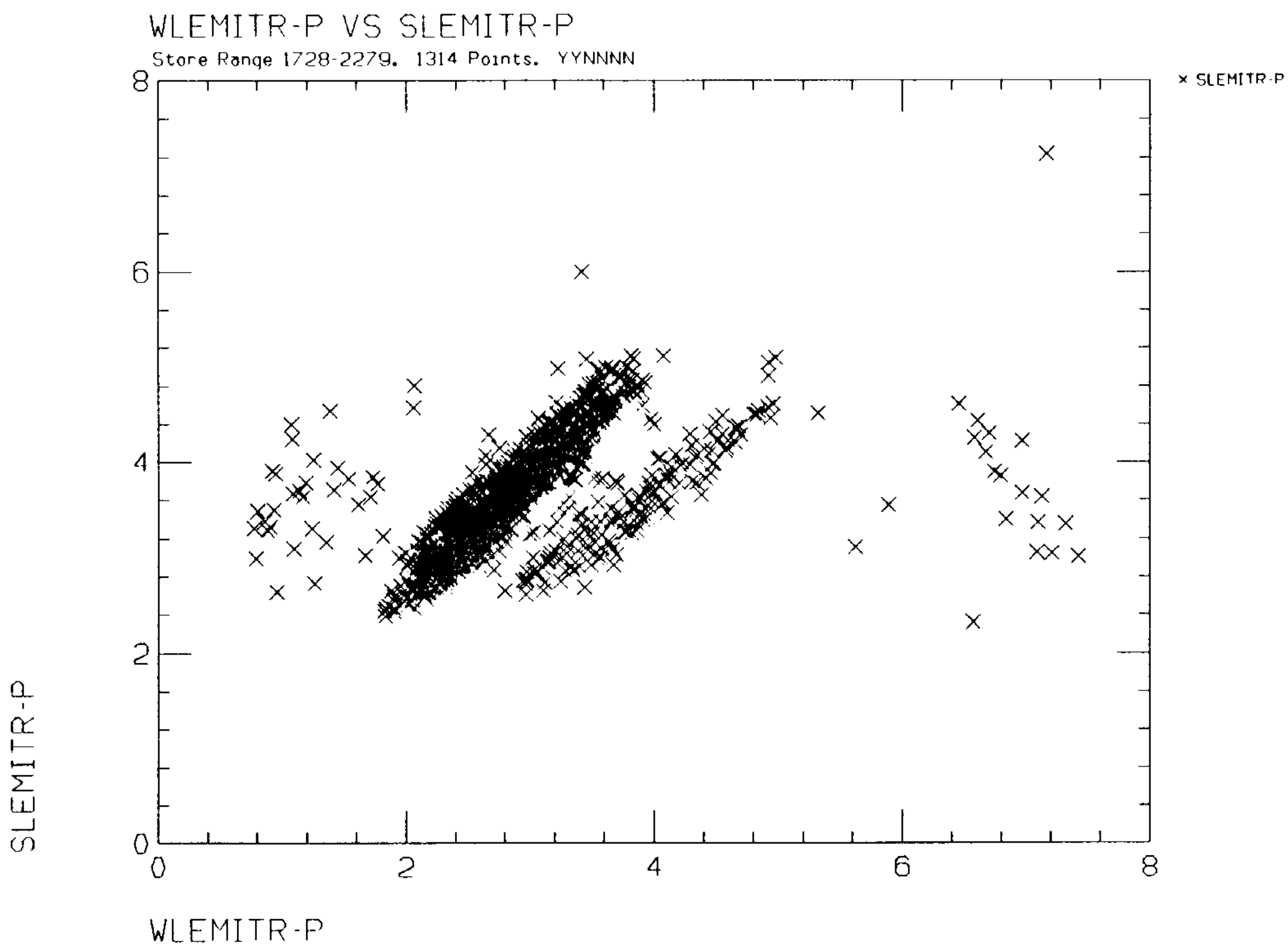
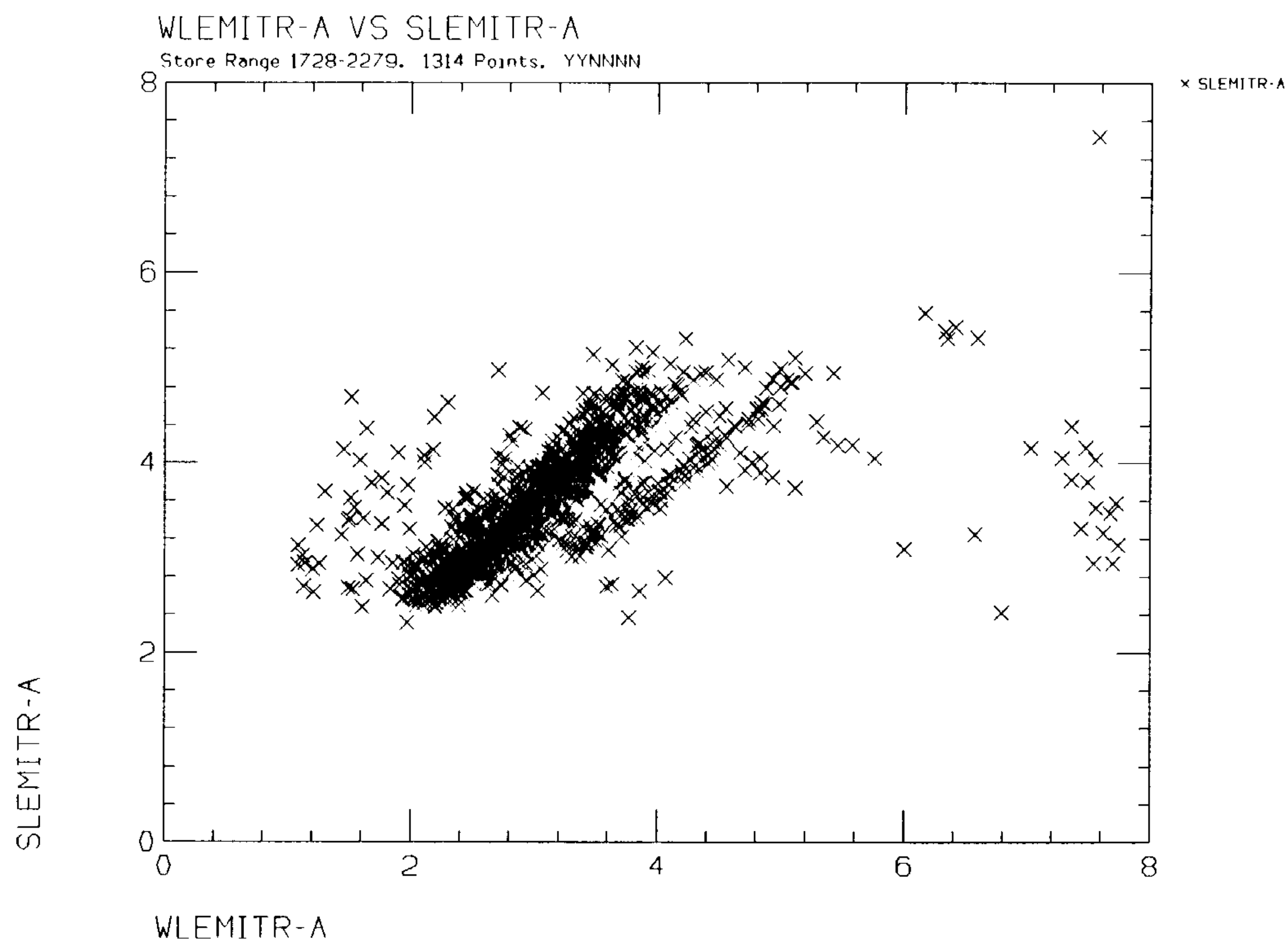

WLEMITR-P VS SLEMITR-P
Store Range 1728-2279. 1314 Points. YYNNNN
× SLEMITR-P
SLEMITR-P
WLEMITR-P
0
2
4
6
8
0
2
4
6
8

Figure 1a



WLEMITR-A VS SLEMITR-A
Store Range 1728-2279. 1314 Points. YYNNNN
× SLEMITR-A
SLEMITR-A
WLEMITR-A
0
2
4
6
8

Figure 1b

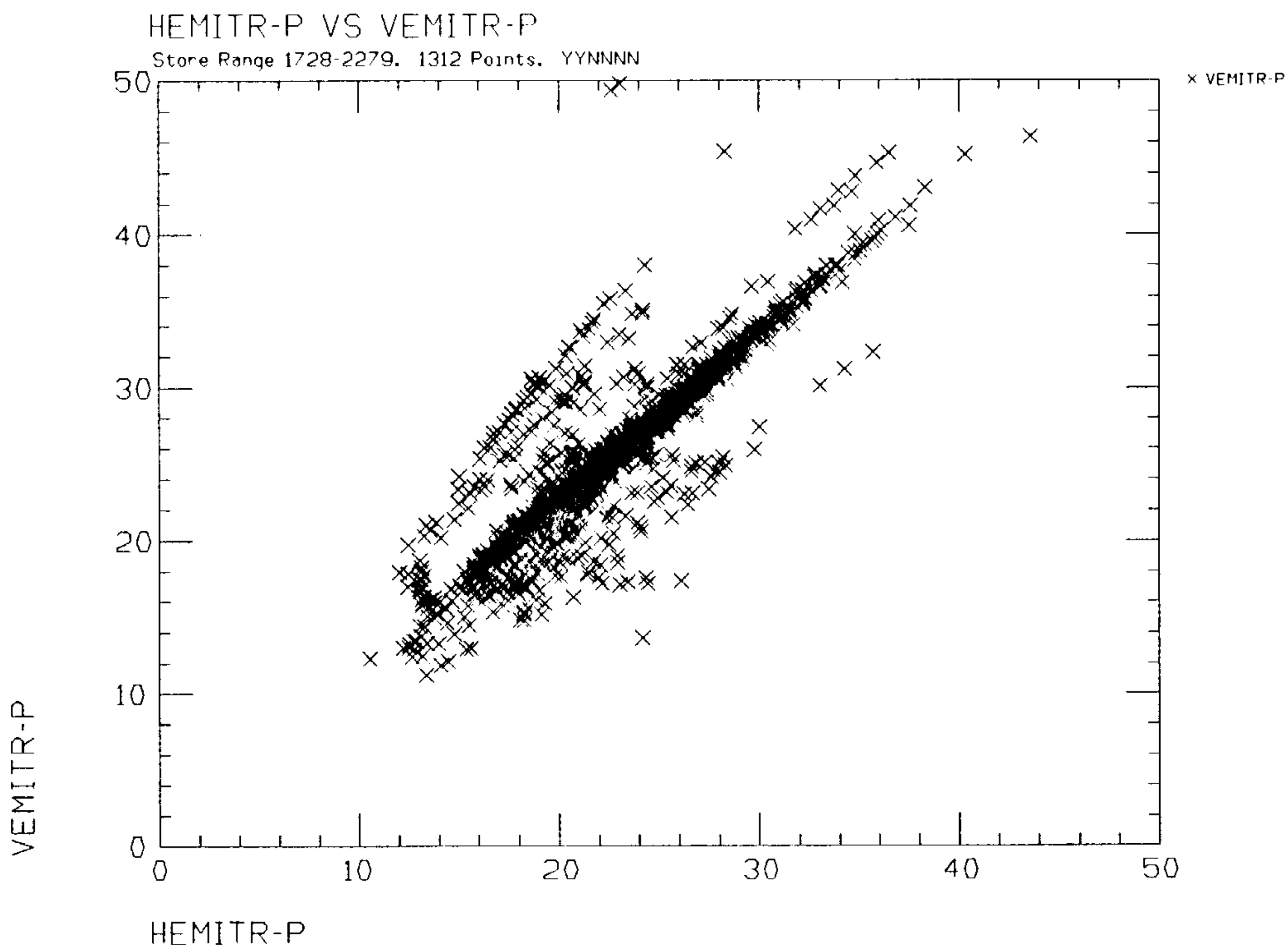
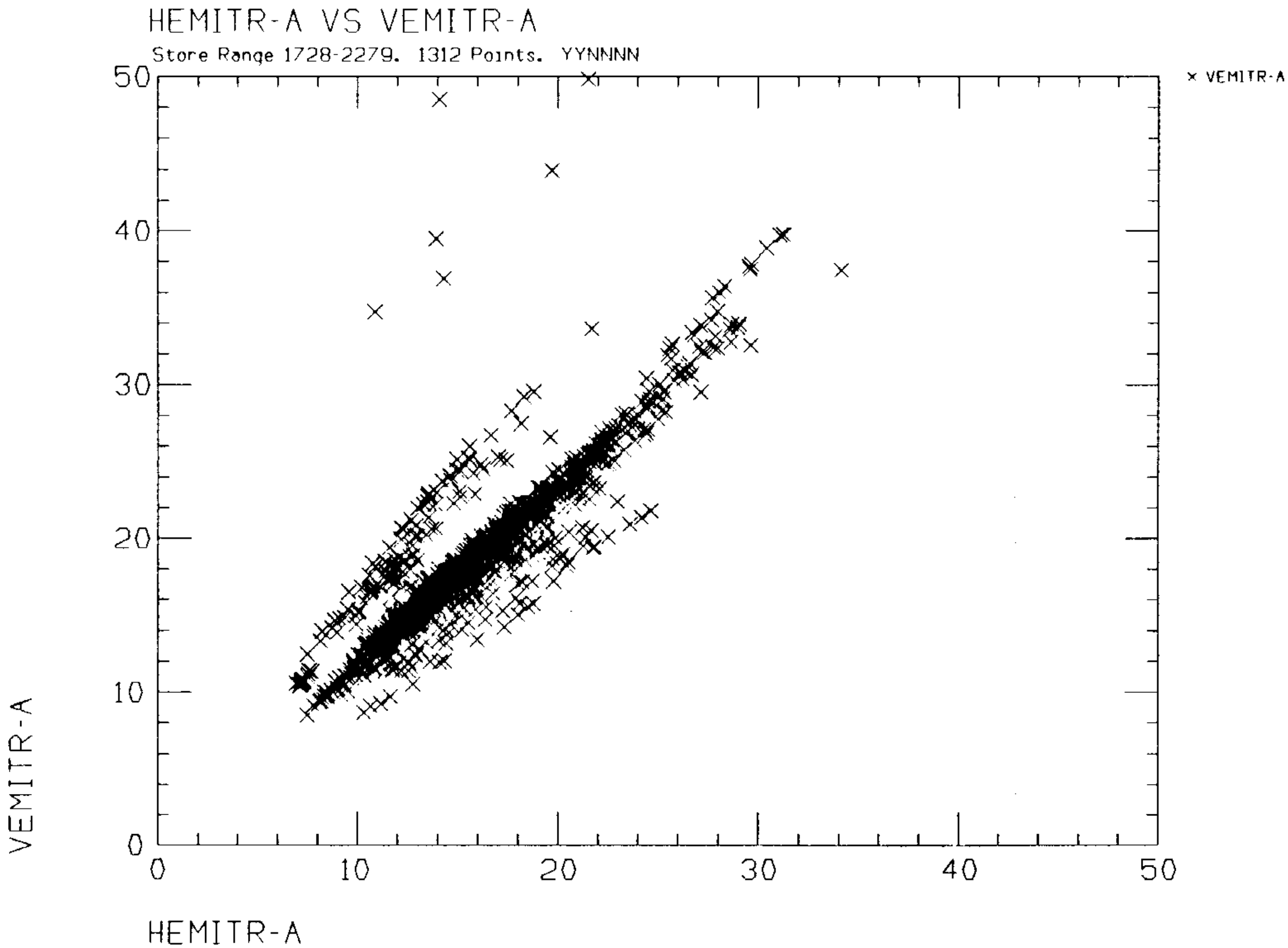

HEMITR-P VS VEMITR-P
Store Range 1728-2279. 1312 Points. YYNNNN
× VEMITR-P
VEMITR-P
HEMITR-P
0
10
20
30
40
50

Figure 1c



HEMITR-A VS VEMITR-A
Store Range 1728-2279. 1312 Points. YYNNNN
× VEMITR-A
0
10
20
30
40
50
VEMITR-A
HEMITR-A

figure 1d

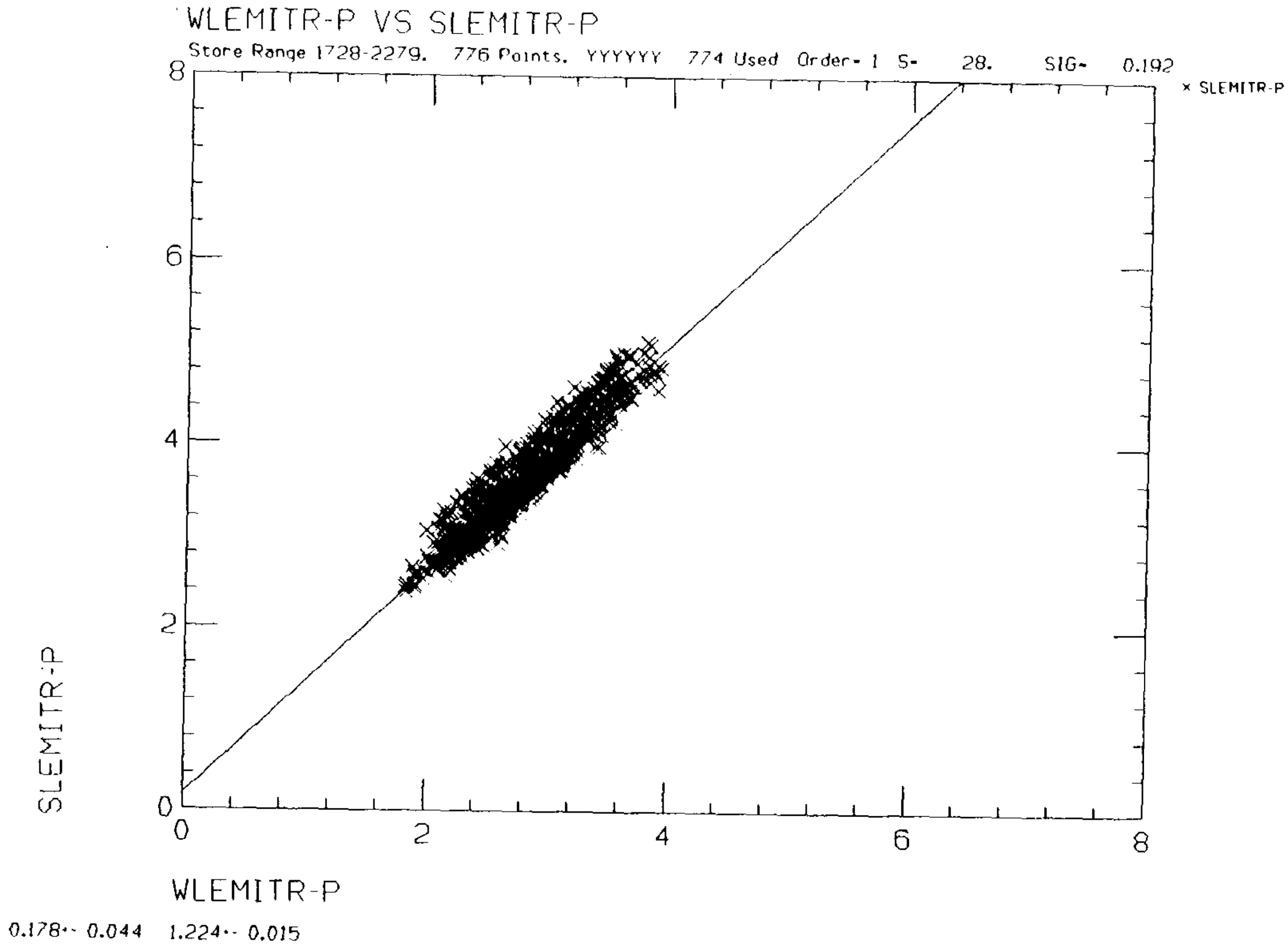
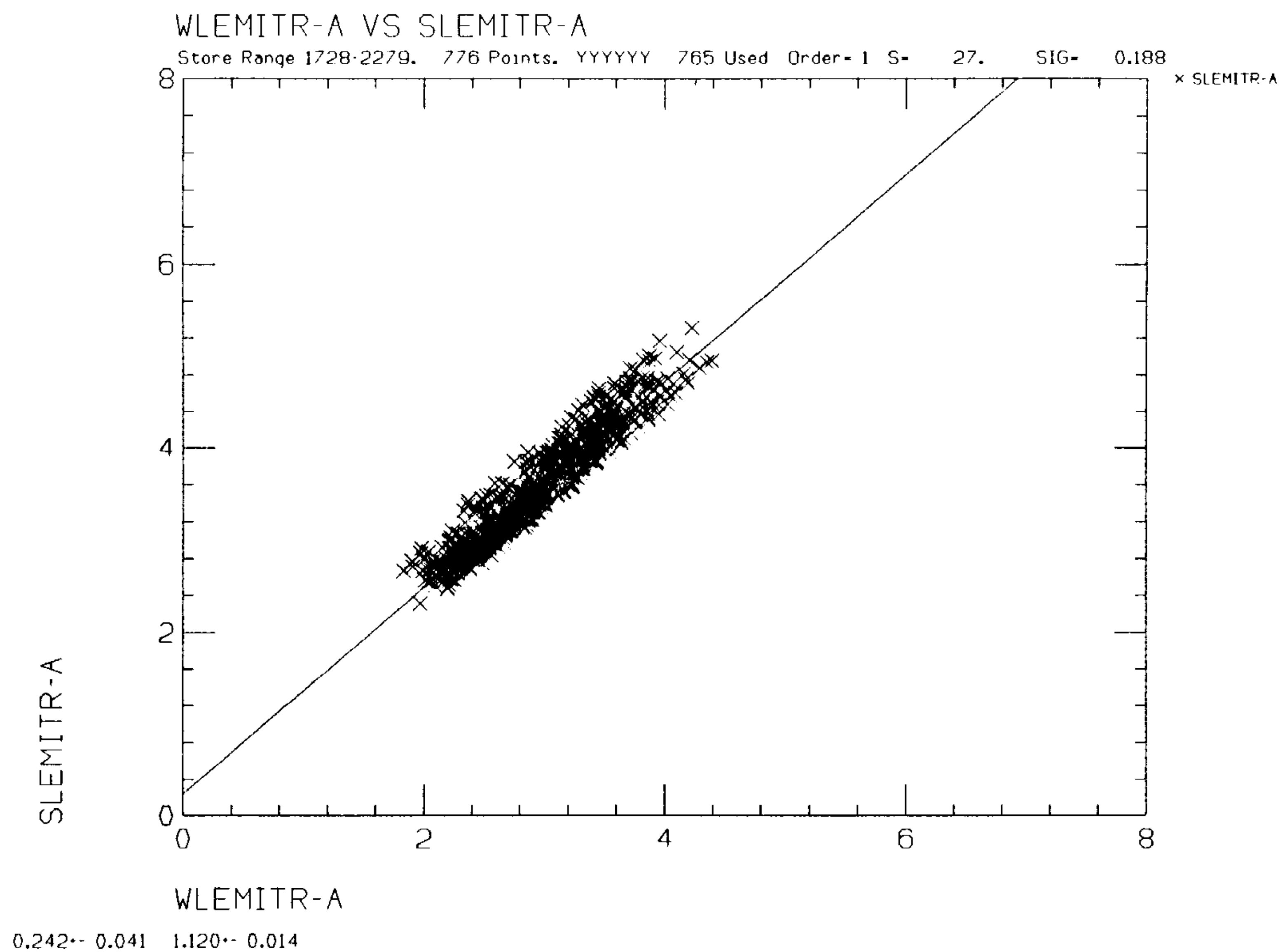

WLEMITR-P VS SLEMITR-P
Store Range 1728-2279. 776 Points. YYYYYY 774 Used Order= 1 S= 28. SIG= 0.192
× SLEMITR-P
SLEMITR-P
WLEMITR-P
0 2 4 6 8
0 2 4 6 8
0.178+- 0.044 1.224+- 0.015

Figure 2a



WLEMITR-A VS SLEMITR-A
Store Range 1728-2279. 776 Points. YYYYYY 765 Used Order= 1 S= 27. SIG= 0.188
× SLEMITR-A
0
2
4
6
8
SLEMITR-A
WLEMITR-A
0.242+- 0.041 1.120+- 0.014

figure 2b

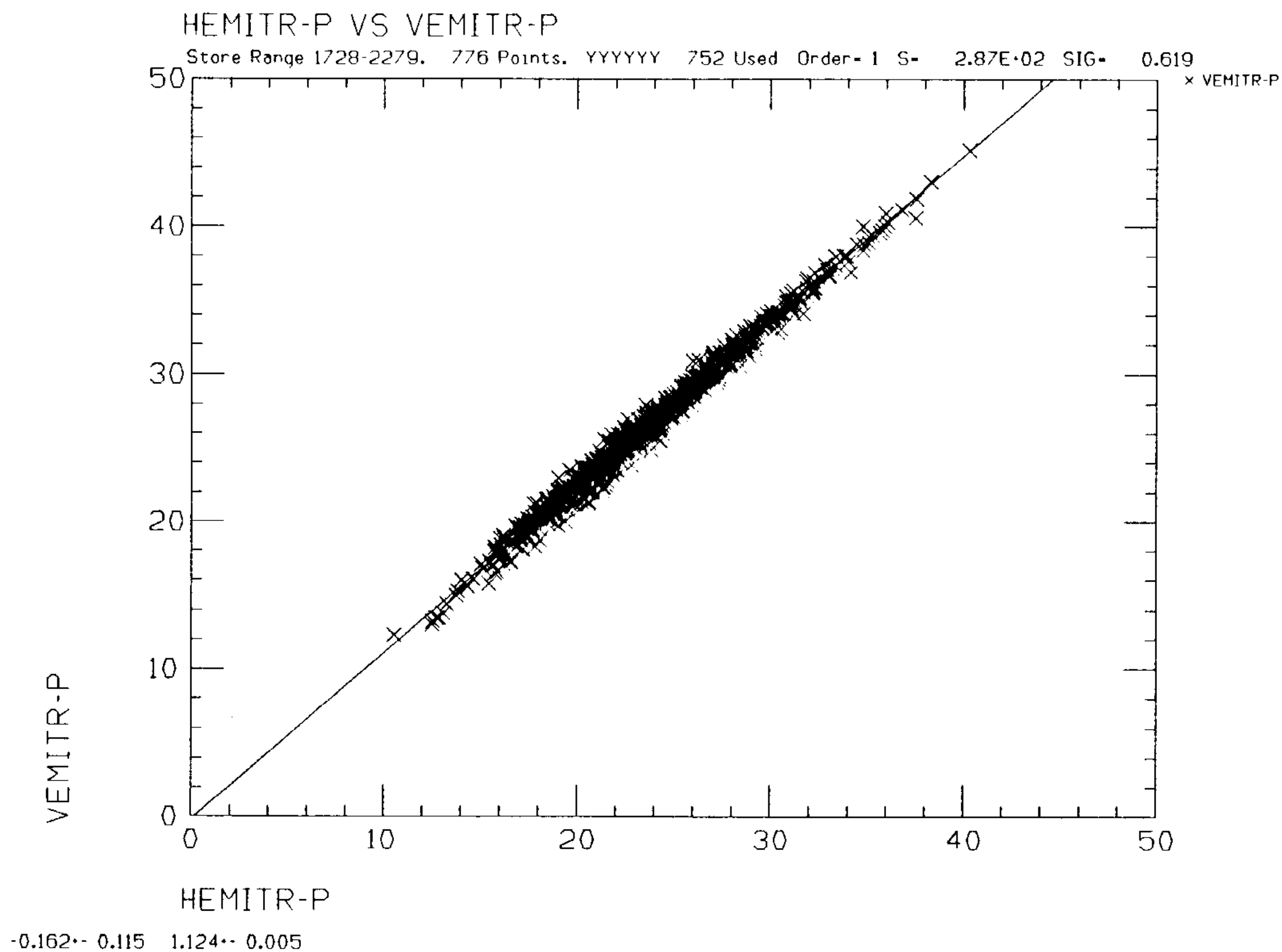
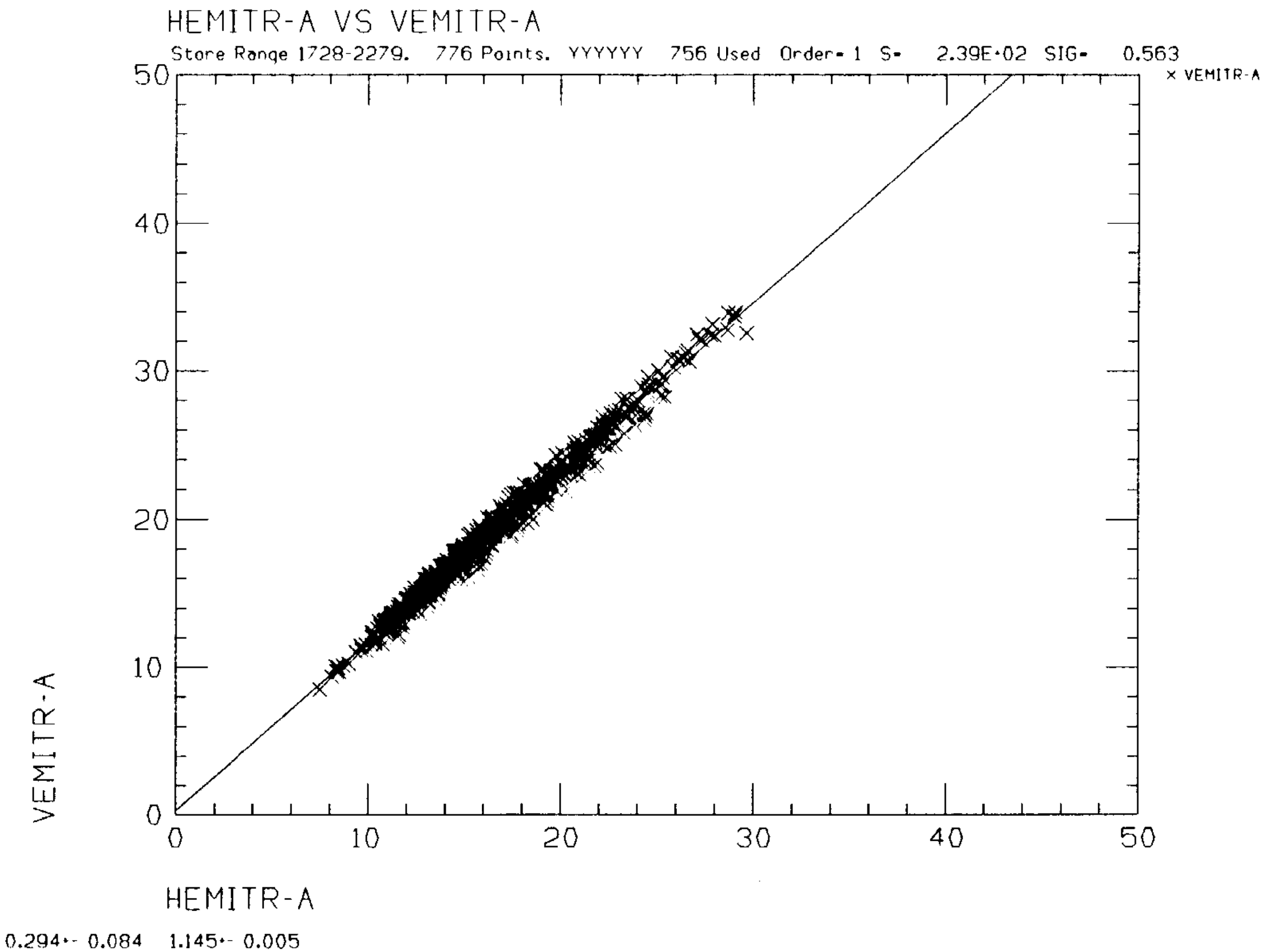
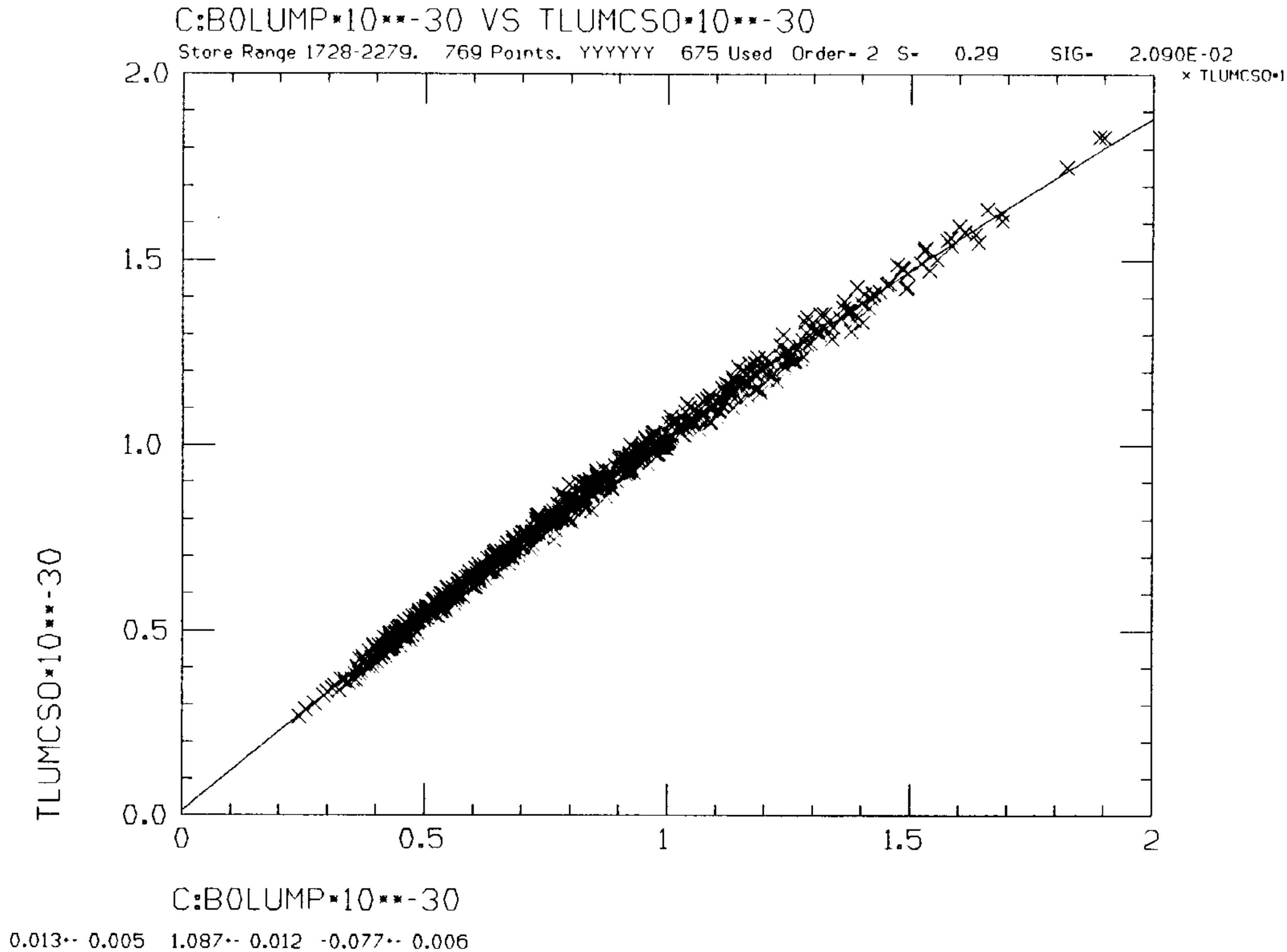

HEMITR-P VS VEMITR-P
Store Range 1728-2279. 776 Points. YYYYYY 752 Used Order= 1 S= 2.87E-02 SIG= 0.619
× VEMITR-P
50
40
30
20
10
0
0
10
20
30
40
50
VEMITR-P
HEMITR-P
-0.162+- 0.115 1.124+- 0.005

Figure 2c



HEMITR-A VS VEMITR-A
Store Range 1728-2279. 776 Points. YYYYYY 756 Used Order= 1 S= 2.39E+02 SIG= 0.563
× VEMITR-A
50
40
30
20
10
0
VEMITR-A
0
10
20
30
40
50
HEMITR-A
0.294+- 0.084 1.145+- 0.005

Figure 2d



C:BOLUMP*10**-30 VS TLUMCSO*10**-30
Store Range 1728-2279. 769 Points. YYYYYY 675 Used Order= 2 S= 0.29 SIG= 2.090E-02
× TLUMCSO*1C
2.0
1.5
1.0
0.5
0.0
TLUMCSO*10**-30
0
0.5
1
1.5
2
C:BOLUMP*10**-30
0.013+- 0.005 1.087+- 0.012 -0.077+- 0.006

Figure 3

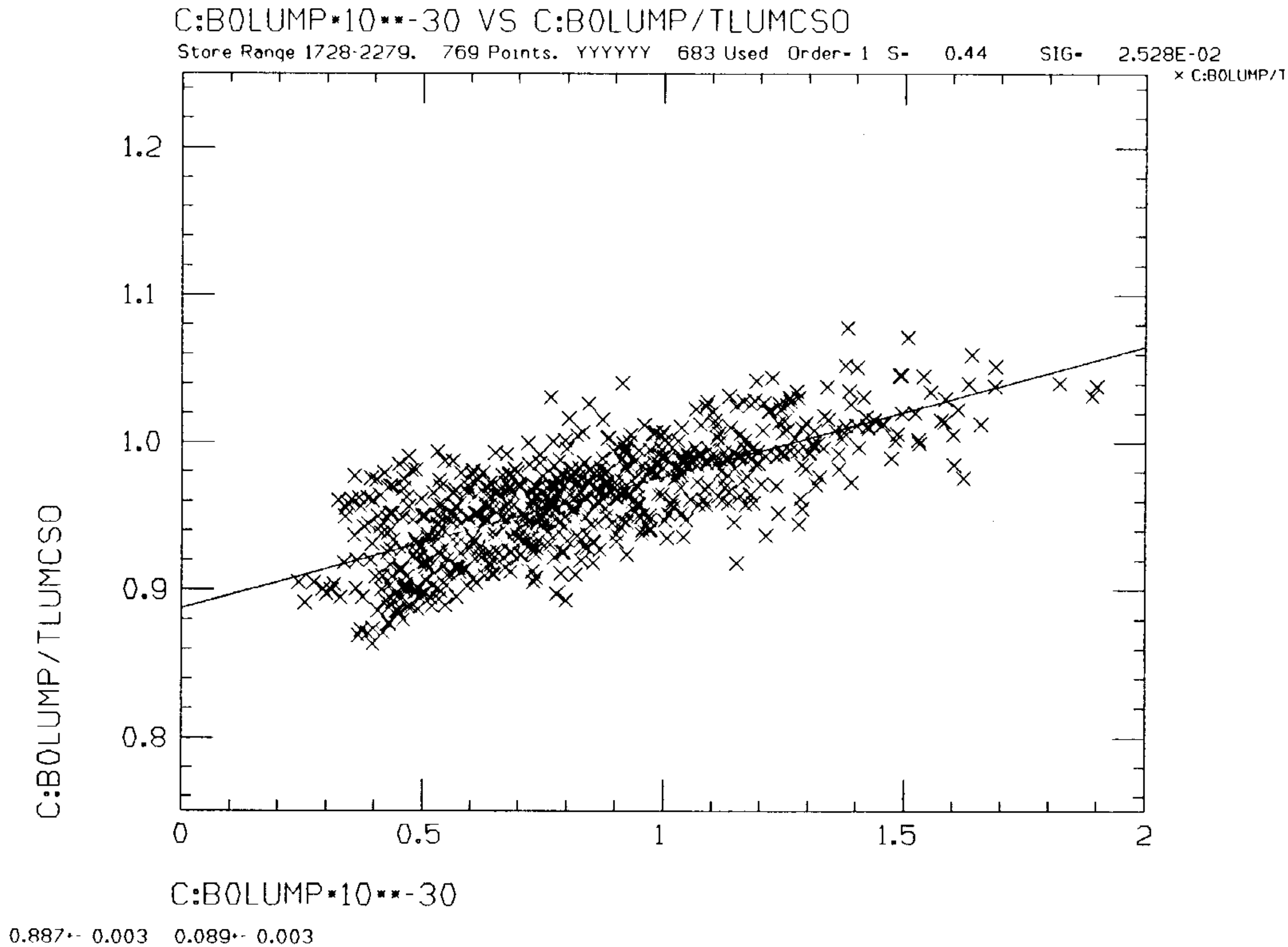

C:BOLUMP*10**-30 VS C:BOLUMP/TLUMCSO
Store Range 1728-2279. 769 Points. YYYYYY 683 Used Order= 1 S= 0.44 SIG= 2.528E-02
× C:BOLUMP/T
1.2
1.1
1.0
0.9
0.8
C:BOLUMP/TLUMCSO
0
0.5
1
1.5
2
C:BOLUMP*10**-30
0.887+- 0.003 0.089+- 0.003

figure 4